

## **North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea**

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### **LONG-TERM GOALS**

The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

### **OBJECTIVES**

Long-range, deep-water acoustic propagation experiments conducted in the North Pacific Ocean over the last twenty years (Worcester and Spindel, 2005) have used controlled sources to transmit to vertical and horizontal line array receivers in order to explore the range and frequency dependence of the fluctuation statistics and coherence (vertical, horizontal, temporal) of resolved ray and mode arrivals

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14. ABSTRACT <b>The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.</b>					
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and of the highly scattered finale first observed in the SLICE89 experiment (Worcester et al., 1994). These experiments reflect the background sound-speed field, the relatively low level of eddy variability, the small-scale sound-speed fluctuations caused by internal tides, internal waves, and density-compensated temperature and salinity variations (spice), and the noise sources found in the relatively benign northeast and north central Pacific Ocean. It is now time to see whether what has been learned in the North Pacific can be applied in a new environment, with differing background sound-speed profiles, much higher eddy energy levels, differing internal wave and spice fields, and differing sources of ambient noise.

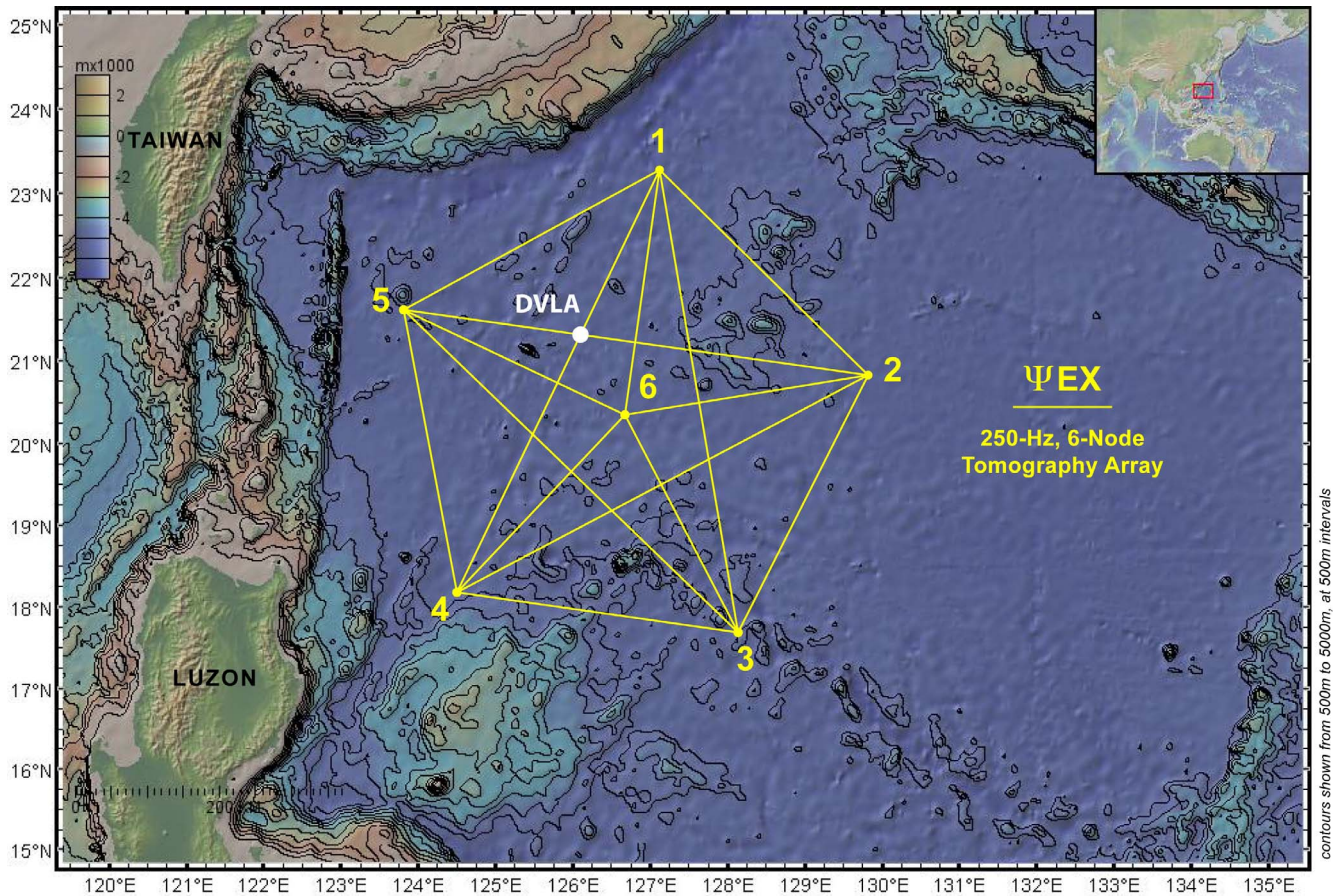
The experiments in the North Pacific have for the most part, although not entirely, also been at very long ranges of 1000 km or more. Simulations suggest that at these long ranges the detailed physics of the scattering processes tend to become less important, as the signals undergo multiple scattering. It is time to move to somewhat shorter ranges, at which the detailed physics of the scattering processes can be better elucidated.

In order to address these issues, our experimental efforts have shifted to the oceanographically complex and highly dynamic northern Philippine Sea. A short-term Pilot Study/Engineering Test was conducted during April-May 2009 (PhilSea09). We are currently preparing for a large-scale, one-year-long, acoustic propagation experiment in the Philippine Sea during 2010–2011 (PhilSea10). The specific objectives are to (i) understand the impacts of fronts, eddies, and internal tides on acoustic propagation in this highly variable region, (ii) determine whether acoustic methods, together with satellite, glider and other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improve our understanding of the basic physics of scattering by small-scale oceanographic variability due to internal waves and spice, and (iv) characterize the ambient noise field, particularly its variation over the year and its depth dependence.

## **APPROACH**

For the 2010–2011 Philippine Sea Experiment (PhilSea10), a new, water-column-spanning Distributed Vertical Line Array (DVLA) receiver has been developed (Worcester et al., 2009). It will be embedded within a six-element ocean acoustic tomography array (Fig. 1). Transmissions from the tomographic sources to the DVLA will be used to study acoustic propagation and scattering in this strongly range-dependent, deep-water region. The tomographic measurements, when combined with satellite and other in situ measurements and with ocean models, will help characterize the baroclinic and barotropic structure of the rapidly varying environment in the northern Philippine Sea, providing an eddy-resolving, 4-D sound-speed field for use in making acoustic predictions.

The new DVLA will allow both modal and ray-based analyses of the propagation. The acoustic propagation experiments that have been conducted in recent years have been constrained by the lack of vertical line array receivers capable of spanning the full water column in deep water. To our knowledge a fully water-column-spanning array has never been deployed in deep water, although such arrays are required to enable the separation of high-order acoustic modes using spatial filtering and to fully characterize the acoustic time fronts found in deep water propagation. We have developed a novel approach using distributed, self-recording hydrophones with timing and scheduling provided by a small number of specially modified versions of our Simple Tomographic Acoustic Receiver (STAR)



**Figure 1. Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of five 250-Hz acoustic transceivers arranged in a pentagon with a sixth transceiver in the center (T1, T2, ... T6) and a new DVLA receiver. The array radius is approximately 330 km.**

data acquisition system and controller, called D-STARS. The enabling technologies for this approach are (i) the availability of flash memory modules that can store several gigabytes of data and be located in a small pressure case at each hydrophone, making it unnecessary to transfer acoustic data from the hydrophone to the central controller for storage, and (ii) inductive modems that allow low-bandwidth communication for command, control, and time synchronization between the D-STAR controllers and the Hydrophone Modules over standard 3 x 19 jacketed oceanographic mooring wire. The DVLA is modular, made up of 1000-m long subarrays, each of which has one D-STAR and roughly 30 distributed, internally-recording Hydrophone Modules that clamp on the mooring wire.

## WORK COMPLETED

**Acoustic Thermometry.** The analysis of the nearly decade-long time series of acoustic measurements of large-scale, depth-averaged temperature in the North Pacific Ocean obtained by the Acoustic Thermometry of Ocean Climate (ATOC) and NPAL projects has been completed, in collaboration with B. Dushaw (APL-UW). The measured travel times were compared with travel times derived from four independent estimates of the North Pacific: (i) climatology, as represented by the World Ocean Atlas 2005 (WOA05), (ii) objective maps of the upper ocean temperature field derived from satellite

altimetry and in situ profiles, (iii) an analysis provided by the Estimating the Circulation and Climate of the Ocean project as implemented at the Jet Propulsion Laboratory (JPL-ECCO), and (iv) simulation results from a high-resolution configuration of the Parallel Ocean Program (POP) model. Modern ocean general circulation models have the vertical resolution needed for acoustic propagation calculations, allowing straightforward comparison of measured and predicted travel times as a first step in using the acoustic data to constrain the models. A paper describing the results has been published in the *Journal of Geophysical Research* (Dushaw et al., 2009).

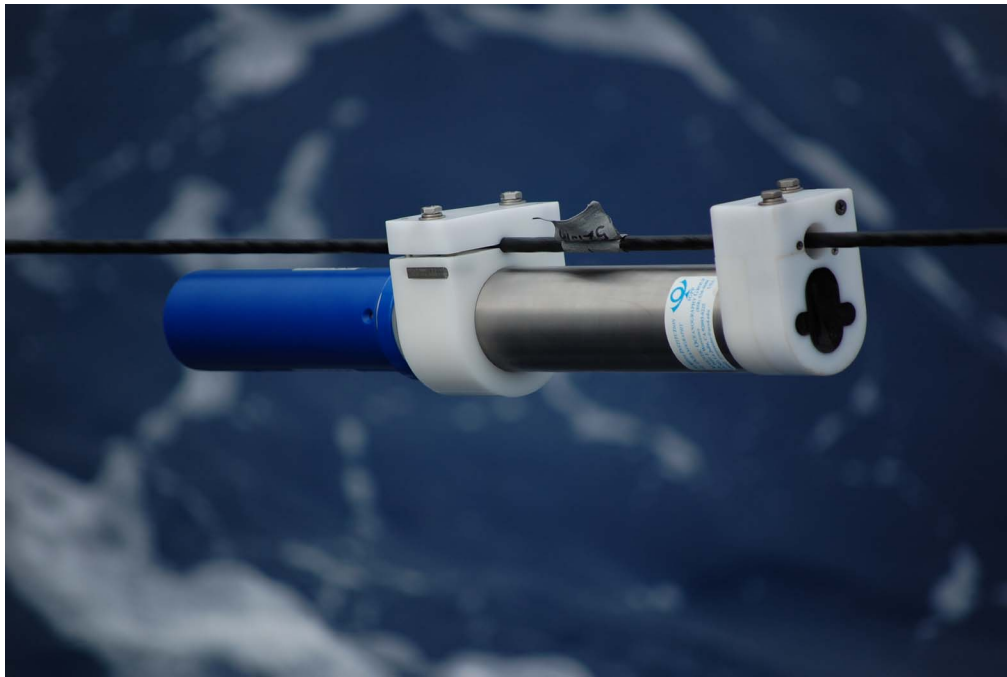
*Shadow-zone arrivals.* The SPICEX component of the 2004–2005 NPAL experiment in the central North Pacific employed moored 250-Hz sources and two vertical line array (VLA) receivers, one spanning the sound-channel axis (Shallow VLA) and one spanning the surface conjugate depth (Deep VLA). The Deep VLA was designed to determine the vertical structure of the acoustic energy that had previously been observed on bottom-mounted receivers several hundred meters into the geometric shadow zones below cusps (caustics) of the acoustic time fronts (Dushaw et al., 1999). L. Van Uffelen, who was supported by an ONR Graduate Traineeship, compared the shadow-zone arrivals seen in the 250-Hz receptions on the VLA receivers in SPICEX with parabolic equation (PE) simulations for sound-speed fields with and without internal-wave variability. The first paper describing her results has been published in the *Journal of the Acoustical Society of America* (Van Uffelen et al., 2009a). A second manuscript has been submitted describing how changes in upper-ocean structure over the course of the experiment affected the shadow-zone arrivals (Van Uffelen et al., 2009b). Ms. Van Uffelen successfully defended her Ph.D. thesis in August 2009.

*2009 NPAL Philippine Sea Pilot Study/Engineering Test (PhilSea09).* PhilSea09 was a coordinated effort involving contributions from investigators in the ONR Ocean Acoustics and Undersea Surveillance Programs. The strategy was to instrument a single acoustic path, between locations T1 and the DVLA, in the larger array planned for PhilSea10 (Fig. 1). The objectives were (i) to obtain an initial look at deep-water acoustic propagation and ambient noise in the northern Philippine Sea, with special emphasis on issues of interest to the Undersea Surveillance Program and on using long duration transmissions to study temporal variability, and (ii) to test the equipment planned for use in 2010–2011 under actual operating conditions. A 225–325 Hz Teledyne Webb Research Corporation (WRC) swept-frequency source was moored at location T1. The newly-developed DVLA was 185.126 km from T1. The DVLA had two, 1000-m long subarrays, with 30 Hydrophone Modules each (Fig. 2). One subarray spanned the sound-channel axis, and the second subarray spanned the surface conjugate depth. Both moorings remained in place for about one month, while coordinated, ship-based components of the experiment were conducted by A. Baggeroer (MIT), G. D’Spain (MPL-SIO), and J. Mercer (APL-UW). The WRC source and DVLA both functioned properly for the duration of the experiment.

*2010–2011 NPAL Philippine Sea Experiment (PhilSea10).* Following completion of PhilSea09, engineering efforts have focused on the acquisition and/or construction of the additional acoustic transceivers, DVLA subarrays, and other equipment needed for PhilSea10. The six tomographic moorings will have WRC swept-frequency acoustic sources, with integrated STAR controller and data acquisition systems, at a depth of 1050 m. These sources transmit acoustic signals with center frequencies of approximately 250 Hz and bandwidths of approximately 100 Hz. Each WRC acoustic source includes a STAR controller and data acquisition system to provide precise timing and scheduling for the source transmissions and to record the transmissions from the other WRC sources. The DVLA to be deployed in 2010 will consist of five 1000-m long subarrays with a total of 150



Hydrophone Modules, rather than the two 1000-m subarrays with a total of 60 Hydrophone Modules deployed in PhilSea09. The nominal depth of the shallowest (deepest) hydrophone is 180 m (5380 m),



*Figure 2. Hydrophone Module being deployed in the Philippine Sea during spring 2009. The Hydrophone Module has a titanium pressure case and an HTI-90-U hydrophone in a polyethylene sleeve. Each Hydrophone Module includes a precision temperature sensor in order to allow calculation of the sound-speed profile at the DVLA.*

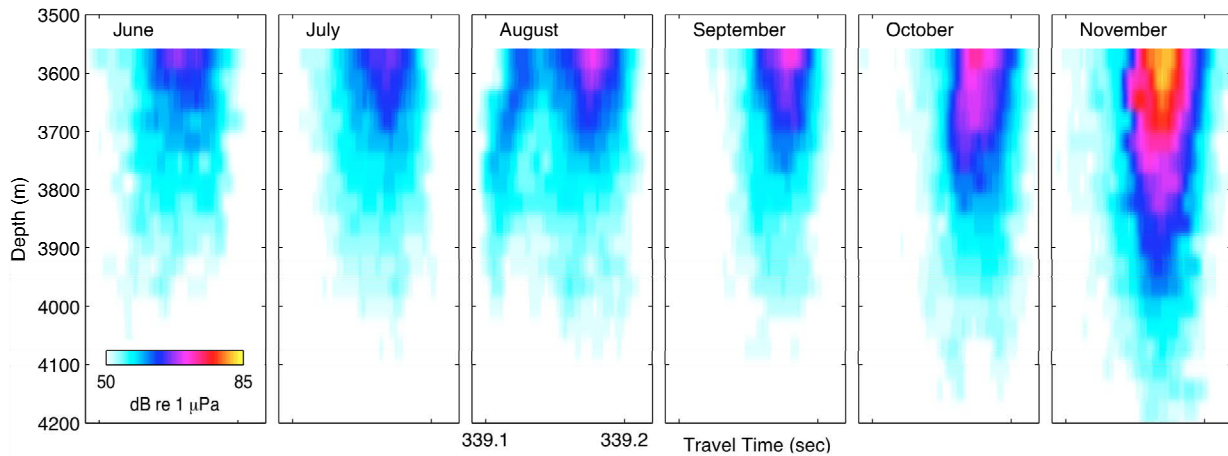
in a water depth of about 5530 m. Our field efforts in PhilSea10 are closely coordinated with the ship-based components of the experiment to be conducted by A. Baggeroer (MIT) and J. Mercer (APL-UW).

## RESULTS

*Acoustic Thermometry.* Over the decade 1996–2006, acoustic sources located off central California (1996–1999) and north of Kauai (1997–1999, 2002–2006) transmitted to receivers distributed throughout the northeast and north central Pacific. The acoustic travel times are inherently spatially integrating, which suppresses mesoscale variability and provides a precise measure of ray-averaged temperature. Daily-average travel times at four-day intervals provided excellent temporal resolution of the large-scale thermal field. The interannual, seasonal, and shorter period variability is large, with substantial changes sometimes occurring in only a few weeks. Linear trends estimated over the decade are small compared to the interannual variability and inconsistent from path to path, with some acoustic paths warming slightly and others cooling slightly. Comparison of the measured travel times with travel times derived from four independent estimates of the North Pacific show that WOA05 is a better estimate of the time-mean hydrography than either the JPL-ECCO or the POP estimates, both of which proved incapable of reproducing the observed acoustic arrival patterns. The comparisons of time

series provide a stringent test of the large-scale temperature variability in the models. The differences are sometimes substantial, indicating that acoustic thermometry data can provide significant additional constraints for numerical ocean models.

*Shadow-zone arrivals.* Comparisons of acoustic data obtained in the North Pacific from June to November 2004 on vertical line arrays at ranges of 500 and 1000 km from moored 250-Hz sources with simulations incorporating scattering consistent with the Garrett-Munk internal-wave spectrum are able to describe both the energy contained in and vertical extent of deep shadow-zone arrivals, which consistently penetrate as much as 500–800 meters deeper into the water column than would be the case in the absence of internal-wave-induced scattering. Incoherent monthly averages of acoustic time fronts indicate that lower cusps associated with acoustic rays with shallow upper turning points (UTPs), where sound-speed structure is most variable and seasonally dependent, deepen from June to October as the summer thermocline develops (Fig. 3). Surface-reflected rays, or those with near-surface UTPs, exhibit less scattering than those with deeper UTPs. Data collected in November exhibit dramatically more vertical extension than previous months. The depth to which the time fronts extend is a complex combination of deterministic changes in the depths of the lower cusps as the range-average profiles evolve with seasonal change and of the amount of scattering, which depends on the mean vertical gradients at the depths of the UTPs.

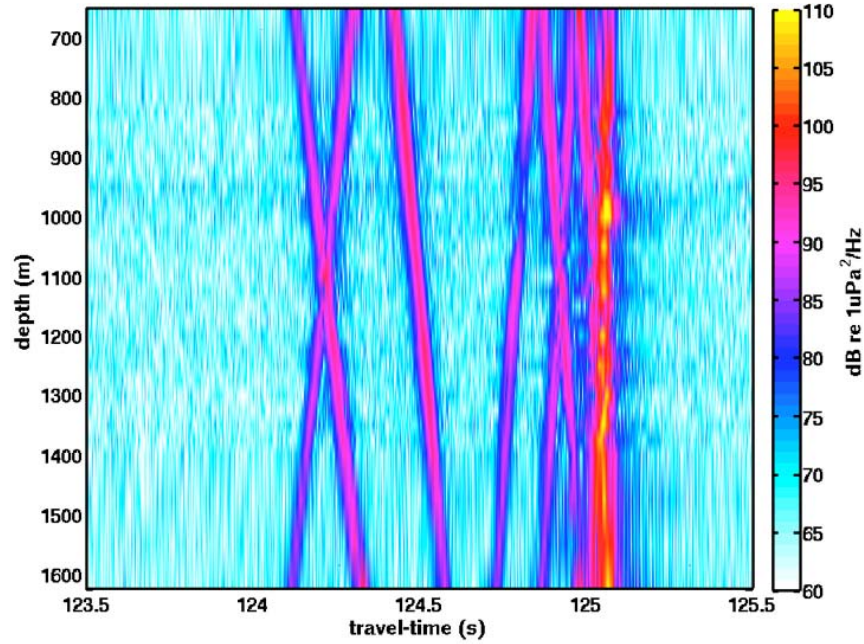


**Figure 3: Monthly incoherent average of measured acoustic intensities (dB re 1  $\mu$ Pa) as a function of travel time and hydrophone depth for one of the time front cusps at the 500-km range, showing dramatic deepening of the cusp in November 2004.**

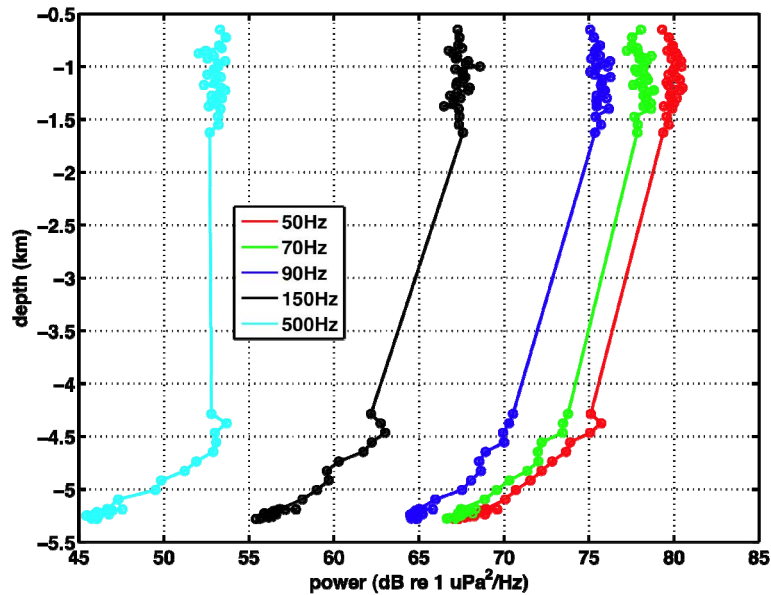
*2009 NPAL Philippine Sea Pilot Study/Engineering Test (PhilSea09).* Processing of the linear frequency-modulated (LFM) transmissions from the 225–325 Hz WRC swept-frequency source on mooring T1 as recorded on the DVLA yielded acoustic time fronts with high signal-to-noise ratios (Fig. 4). As might be expected given the relatively short range (185.126 km), there is little evidence of a highly-scattered finale in the time fronts on the axial subarray. Analysis of the fluctuations in the received signals is only now just beginning.

The DVLA was also programmed to record during periods when no signals were present in order to characterize the low-frequency ambient noise field. The *minimum* omnidirectional ambient noise levels during PhilSea09 decrease significantly below the surface conjugate depth at frequencies from 50 to

500 Hz (Fig. 5). Similar behavior had previously been observed in the central North Pacific (Gaul et al., 2007). The minimum noise levels presumably correspond to times when wind speeds are low and surface conditions are calm, so that there is little locally-generated noise. Further analysis is required in order to confirm this hypothesis, however.



*Figure 4. Acoustic time front on the DVLA subarray spanning the sound-channel axis for a transmission from the acoustic source on mooring T1, at a range of 185.126 km, during PhilSea09. The recording was made on 5 April 2009 at 18:02:00 UTC.*



*Figure 5. Minimum omnidirectional ambient noise levels measured on the DVLA during PhilSea09 at 50, 70, 90, 150, and 500 Hz, showing substantial decreases in noise levels below the surface conjugate depth at all frequencies.*



## IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior. The data indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

## TRANSITIONS

*Simple Tomographic Acoustic Receiver (STAR)*. The Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, and the Alfred-Wegener-Institut fuer Polar- Und Meeresforschung (AWI) in Bremerhaven, Germany, are funded in the framework of the European Union DAMOCLES and/or ACOBAR projects to develop an ocean acoustic tomography and acoustic navigation system in Fram Strait, between Svalbard and Greenland at about 78°50'N (Sagen et al., 2007). NERSC previously purchased two STARs from my group and a swept-frequency acoustic source (190–290 Hz) from Teledyne Webb Research, which in turn ordered a third STAR from my group to serve as the controller for the source. The source and stand-alone STAR receivers were successfully deployed from August 2008 to August 2009 on the eastern side of Fram Strait, with assistance from my group. Analysis of the data is now in progress. AWI is purchasing an additional WRC/STAR swept-frequency source. NERSC is in the processing of ordering a third WRC/STAR source. All of the source STARs are configured to serve as receivers as well, forming acoustic transceivers. The three transceivers and the two stand-alone STARs are scheduled to be deployed in Fram Strait from summer 2010 to summer 2011.

## RELATED PROJECTS

A large number of investigators and their students are currently involved in research related to the NPAL project, including R. Andrew (APL-UW), A. Baggeroer (MIT), F. J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), B. Dushaw (APL-UW), G. D'Spain (SIO), O. Godin (NOAA/ETL), N. Grigorieva (St. Petersburg State Marine Technical Univ.), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (Univ. Hawaii), J. Mercer (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), B. Powell (Univ. Hawaii), I. Rypina (WHOI), E. Skarsoulis (IACM/FORTH), R. Stephen (WHOI), I. Udovychenkov (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), M. Wolfson (APL-UW), and L. Zurk (Portland State).

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